Intelligent Monitoring System With High Temperature Distributed Fiber Optic Sensor For Power Plant Combustion Processes

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OUTLINE

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I. Introduction

- Next generation power plant
  - Increase boiler efficiency
  - Reduce pollution (such as NO_x → Cancer)
- Smart sensors and intelligent control
- KEY: Distributed High temperature sensing

However, it is a challenge to measure high temperature distributions in an harsh environment

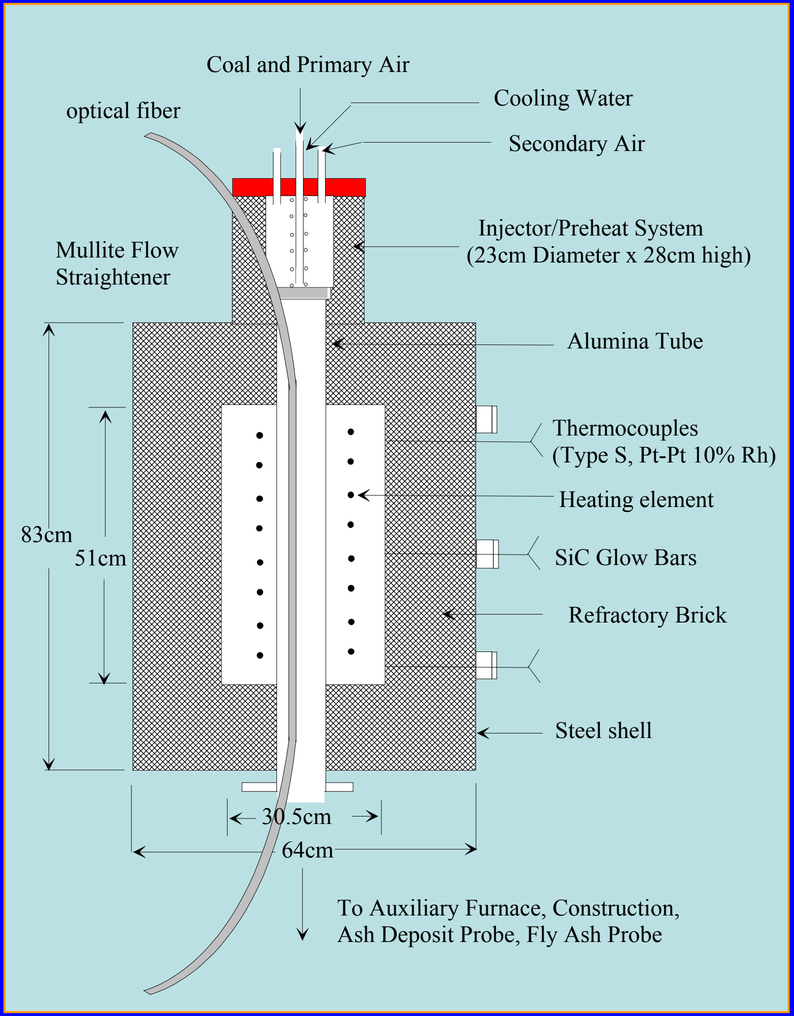
I. Introduction

- **High temperature distributed sensing can play a key role in fuel industry.**
  - Increase boiler efficiency
  - Reduce pollution (such as NO_x → Cancer)
  - Traditional radiation based sensing is not good for distributed sensing.

-- essential in accessing and controlling pollutants at the source

I. Introduction

- **Distributed fiber optic sensor offers following unique features**
  - Multiple locations can be sensed using a single fiber
  - High sensitivity
  - Robust against EM interferences
  - Compact size



I. Introduction

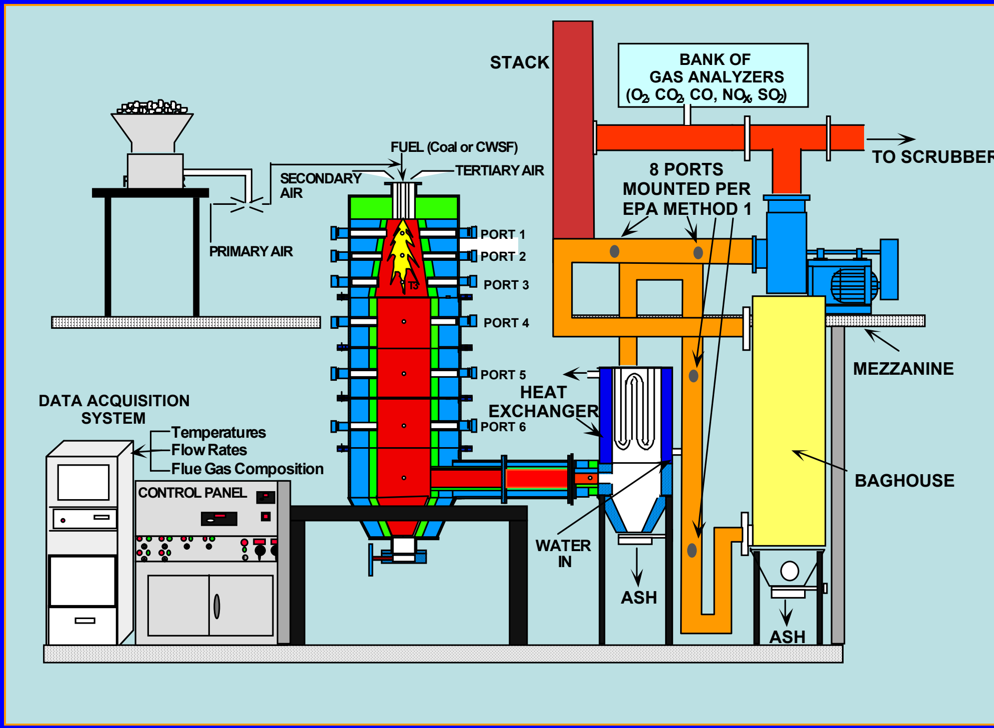
The basic approach in developing the proposed sensor system is in three fold developments:

1. High temperature fiber optical sensors -- 2000 C degree with spatial resolution of 1 cm
2. Distributed parameter system models to map the 3D temperature distribution of the furnace
3. Intelligent monitoring system for real-time monitoring of the 3D temperature distribution

II. Penn State Research Facility

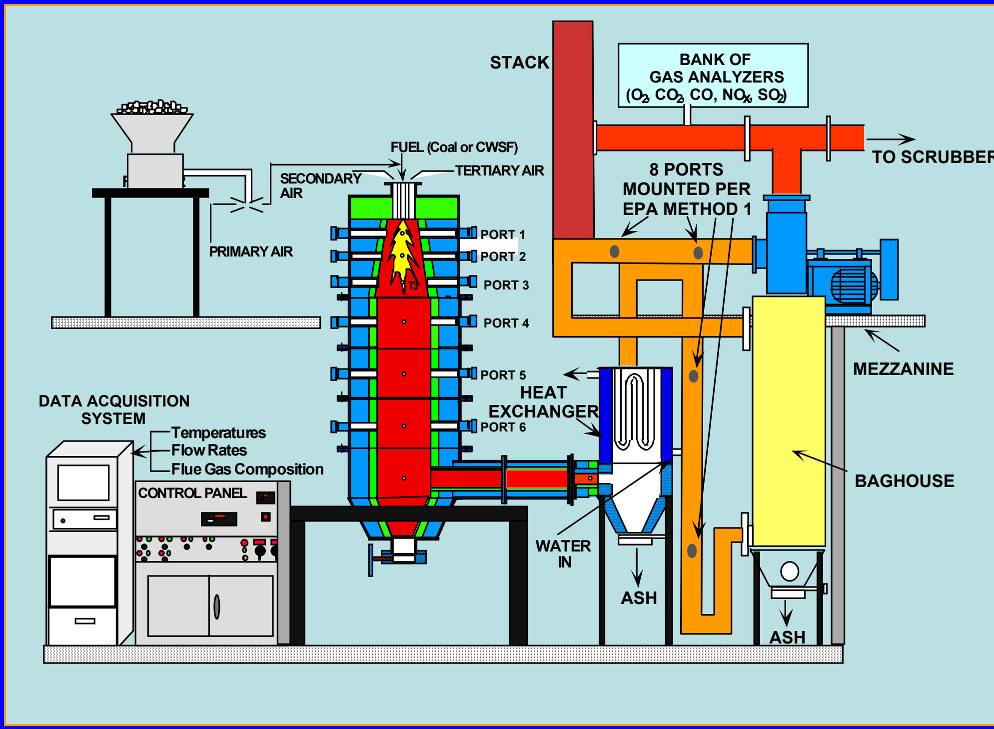
Four types of research boilers are available at the Penn State Energy Institute (EI):

1. The drop-tube reactor (DTR)
2. The down-fired combustor (DFC)
3. The 1,000 lb. steam/h Watertube Research Boiler
4. The 15,000 lb. steam/h Demonstration Boiler System



Distributed parameter System Modeling

- Objectives
  - Simulate combustion for:
    - Demonstration Boiler (3D)
    - Down-Fired Combustor (2D & 3D)
  - Collect T, NO_x & velocity data
    - Compare statistically to determine a correlation between the parameters
- Tools
  - Grid generation via Gambit 2.1
  - Combustion simulation via FLUENT 6.1

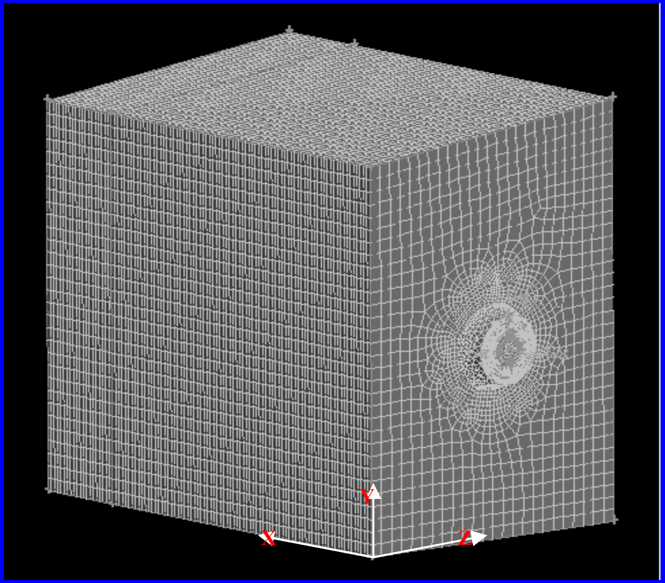


Distributed parameter System Modeling

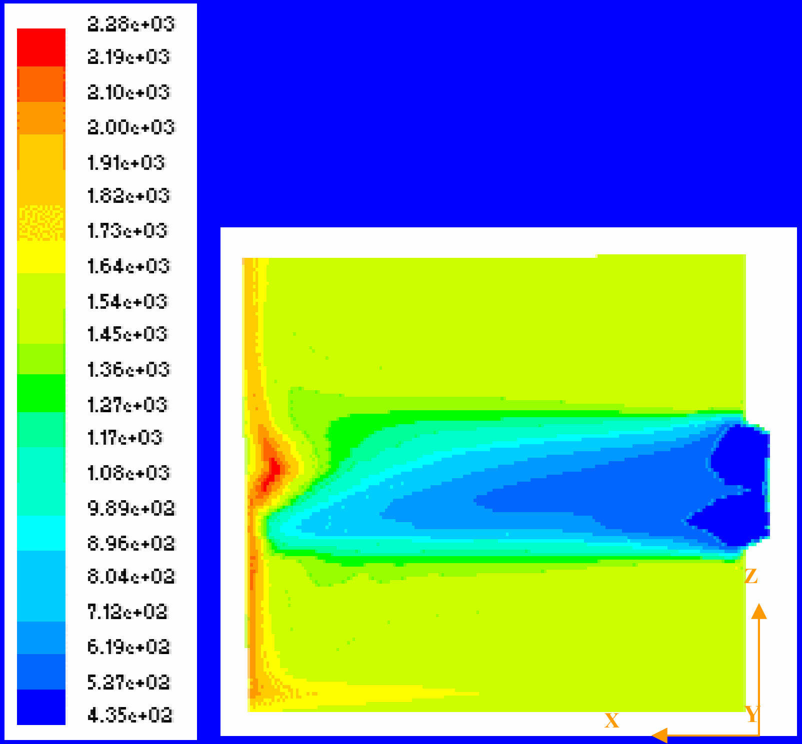
Meshed grid of the demo boiler used in the simulation (nearly 273,000 nodes).

Boiler dimensions (inches):

104 x 72 x 102



Boiler Grid



Temperature contour of the axial plane within the demo boiler.

III. Intelligent System Monitoring

- A 3D Distributed Parameter System model -- a set of partial differential equations for temperature distribution in 3D
- State estimation techniques -- limited by the complexity of the model

  $\Rightarrow$ real-time computation is not feasible for on-line distributed parameter estimation.
- An alternative -- an intelligent monitoring scheme for 3D temperature estimation by using *artificial neural networks*
- The generalization property of NN will result in the mapping of the 1D sensor data into the 3D temperature distribution.

III. Intelligent System Monitoring

Temperature Estimation The method hinges on two premises:

1. An acceptable approximation to the "exact" solution can be obtained by using the following form :

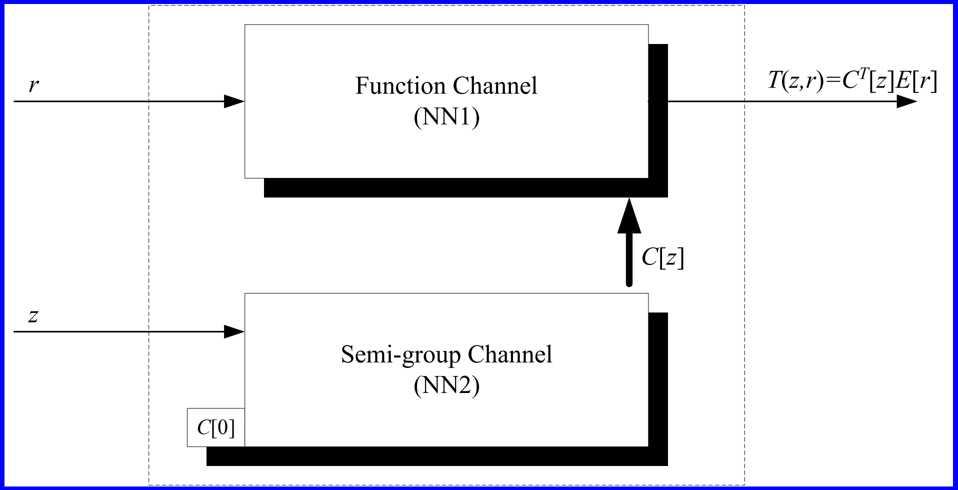
$$T(x, y, z) \cong T(r, z) \cong \sum_{i=1}^{n} C_i(z) E_i(r)$$

n : the number of linearly independent orthonormal basis functions $E_i(r)$, and $C_i(z)$ is a coefficient.

2. The coefficients $\{C_i\}$ of this expansion have a regularity to them, which reflects the physical regularity along the z-axis.

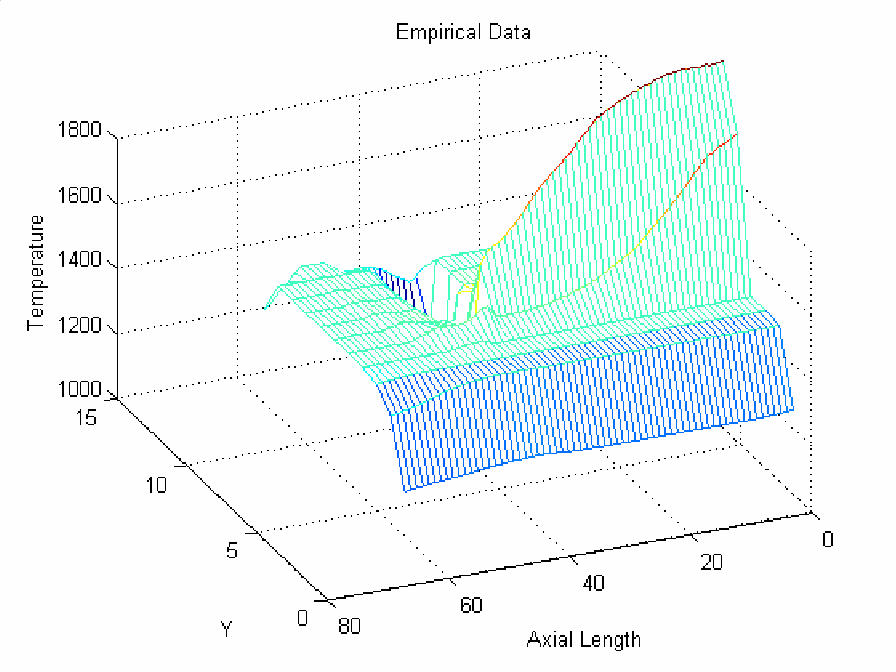
III. Intelligent System Monitoring

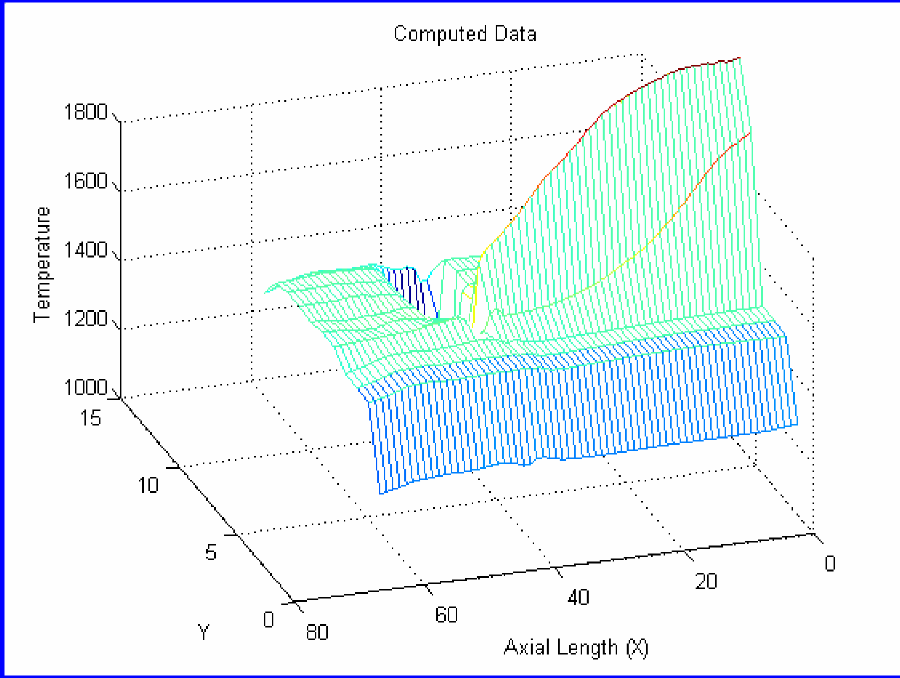
1. Implementation or Function channel -- a set of *n* RBF neural networks,



2. Observation or Semigroup channel -- a recurrent neural network which will be trained to possess a *regularity* feature similar to a Semigroup property,
   i.e., $C(z) = \Phi(z)C(0)$ where, $\Phi(z_1 + z_2) = \Phi(z_1)\Phi(z_2)$

III. Intelligent System Monitoring





Empirical Data of actual furnace

Computed Data of actual furnace

IV. Sensor Development

Fiber gratings based distributed fiber optic sensor

Advantages

High spatial resolution (cm range)
High sensitivity

Limitations

Traditional silica fiber is not good for very high temperature
Grating fabricated by UV will be erased (when > 200 ^{o}C)

Our approach

Fabricate LPG in single crystal sapphire fiber
Sensing up to 2000 ^{o}C.

IV. Sensor Development - continued

- **Why Sapphire Fibers ?**

  - Single Crystals of alpha- Al2O3
  - Super Corrosion Resistance
  - High melting temperature (~ 2050 °C)
  - Good Transparency over wide wavelengths (visible ~ IR)

→ **Excellent Material for High Temperature Sensing**

IV. Sensor Development - continued

- **Technological Challenges**
  - Core Only , Highly Multimoded
  - No Splicing Techniques
  - No Known Photo-sensitivity

► Difficult to use Standard Fiber-Optic Techniques

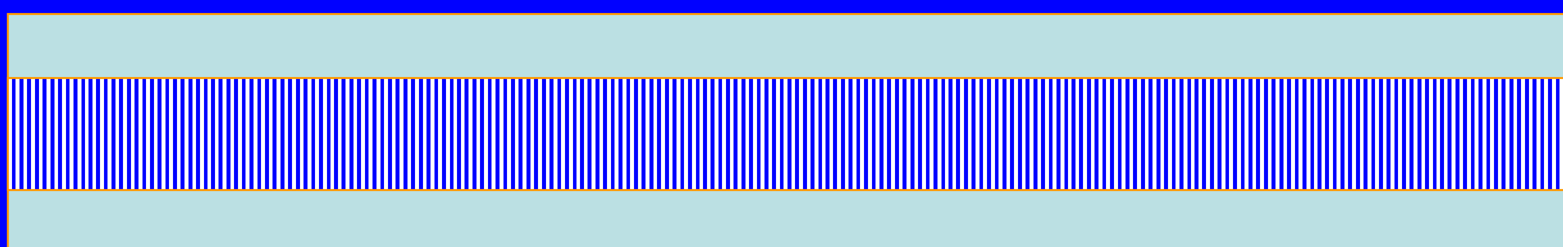
- **Proposed Sapphire Fiber Sensors so far**
  - Black Body Cavity Temperature Sensor
    (R.R.Dils et al., J.Appl.Phys. 1983)
  - Extrinsic Fabry-Perot Interferometer
    (K.A.Murphy et al., SPIE 1588, 1991)

⇒ All were Point-Sensing Sensors

V. Background on long period gratings

- **LPG**
  - Coupling between **CORE** and **CLADDING** modes

$$\beta_{co} - \beta_{cl} = \frac{2\pi n}{\Lambda}$$



V. Background on long period grating (LPG) (Continued)

- **Advantages of using LPG for sensing**
  - **High sensitivity** – small refractive index change induced by temperature variation can result in large wavelength shift

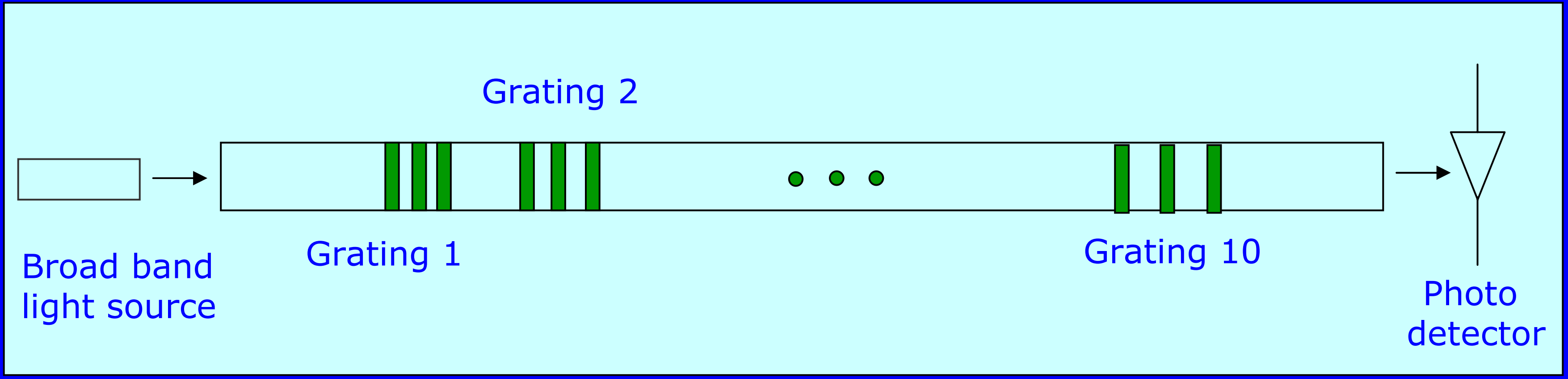
$$\Delta\lambda = \frac{\Delta(n_{co} - n_{cl})}{n_{co} - n_{cl}} \lambda_p$$

  - Quasi-**distributed** sensing
  - **Low insertion loss** (all fiber structure)
  - **Cost effective (single fiber**

V. Background on long period gratings (LPG)
(Continued)

- **How can we make distributed sensors with sapphire fibers ?**
  - No Photo-sensitivity
  - No OTDR-based methods (need a few cm order spatial resolution)

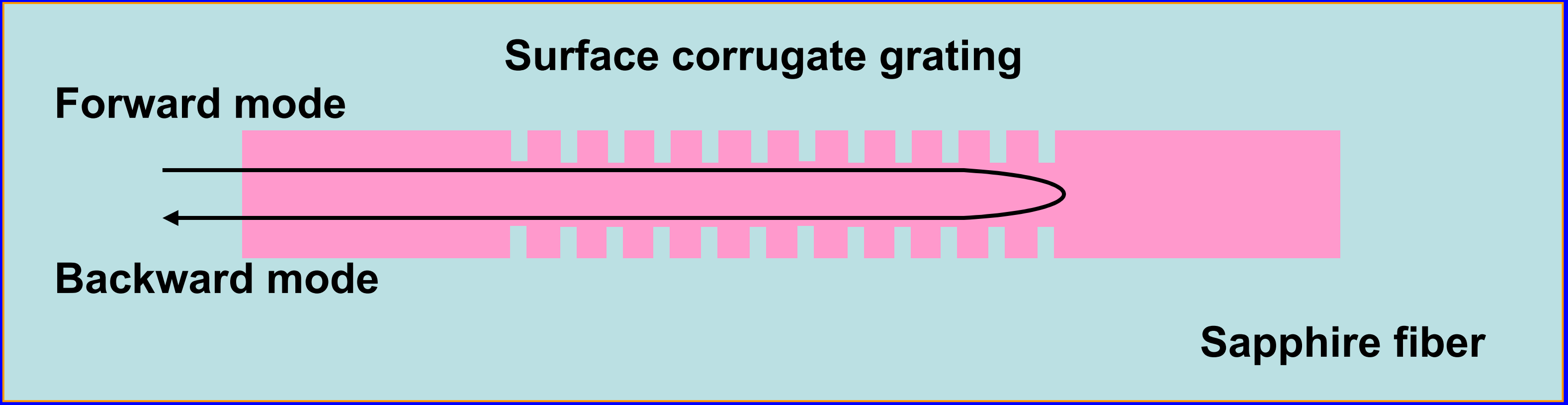
Next section – fabrication methods



VI. Fabrication Methods for In-Fiber Gratings in Sapphire fibers

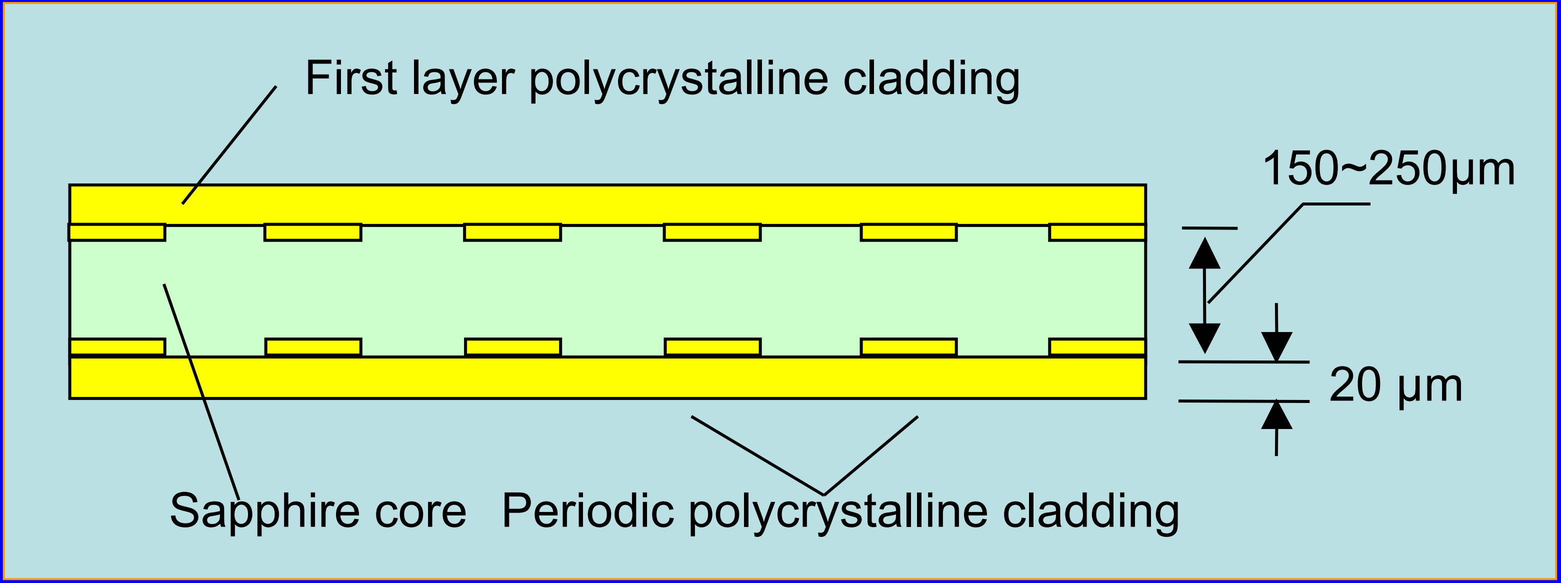
- **6.1 Fabrication by micro-machining (BRAGG Grating)**
  - Coupling between **forward modes** and **backward modes**

$$\Lambda = \frac{\lambda_r}{2 n_{co}^{eff}}$$



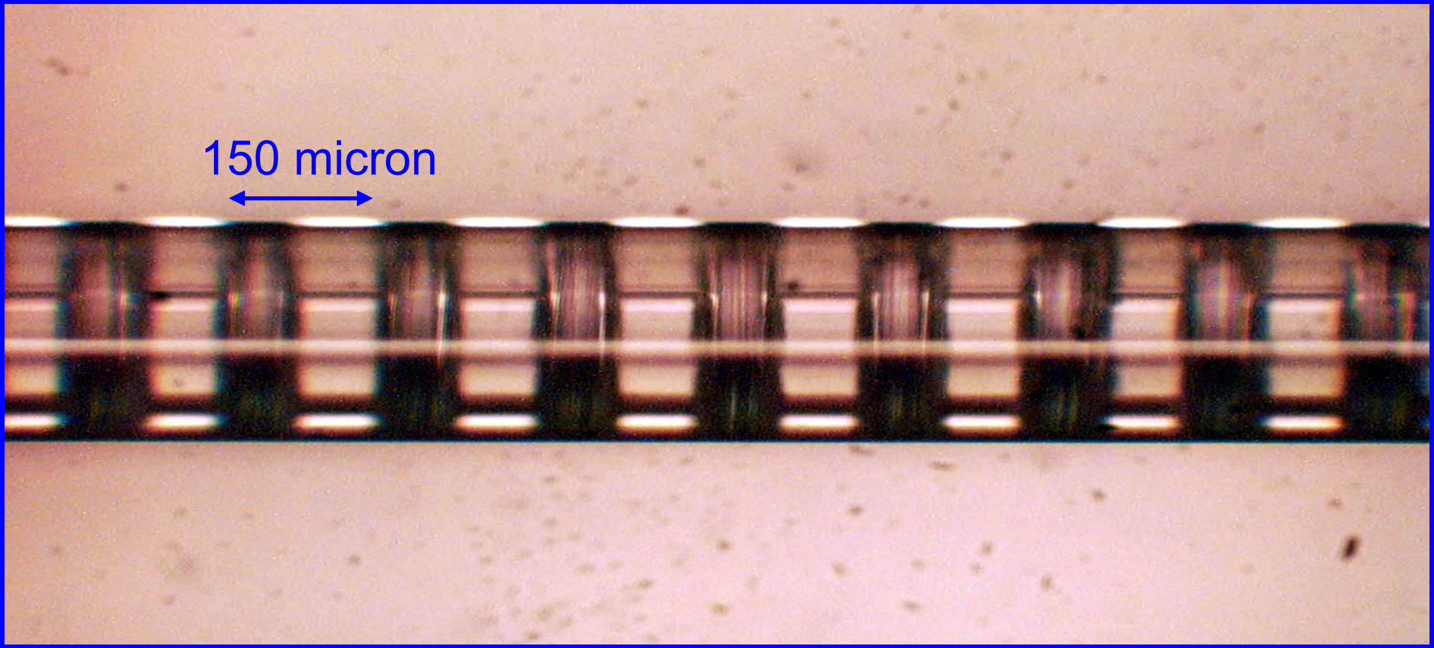
- **6.1 Fabrication by micro-machining (LONG PERIOD GRATING)**
  - Coupling between **core modes** and **cladding** modes

$$\Lambda = \frac{2\pi n}{\beta_{co} - \beta_{cl}}$$



VI. Fabrication Methods for In-Fiber Gratings in Sapphire fibers - continued

- **Mechanical Dicing**

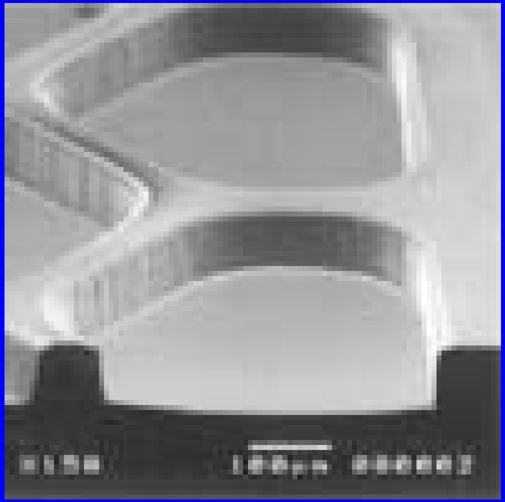


Fabricated corrugated gratings in single crystal sapphire fiber by precise dicing

VI. Fabrication Methods for In-Fiber Gratings in Sapphire fibers - continued

- **Plasma Etching (ICP-RIE)**

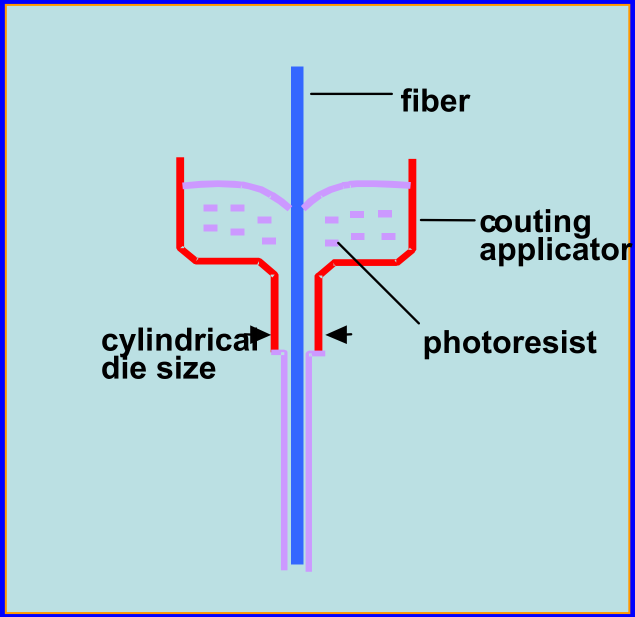
Gases : Cl_2/BCl_3 50:50
Etch rate : ~ 350 nm/min
(Y.J.Sung et al, Materials Science and Engineering, 2001)

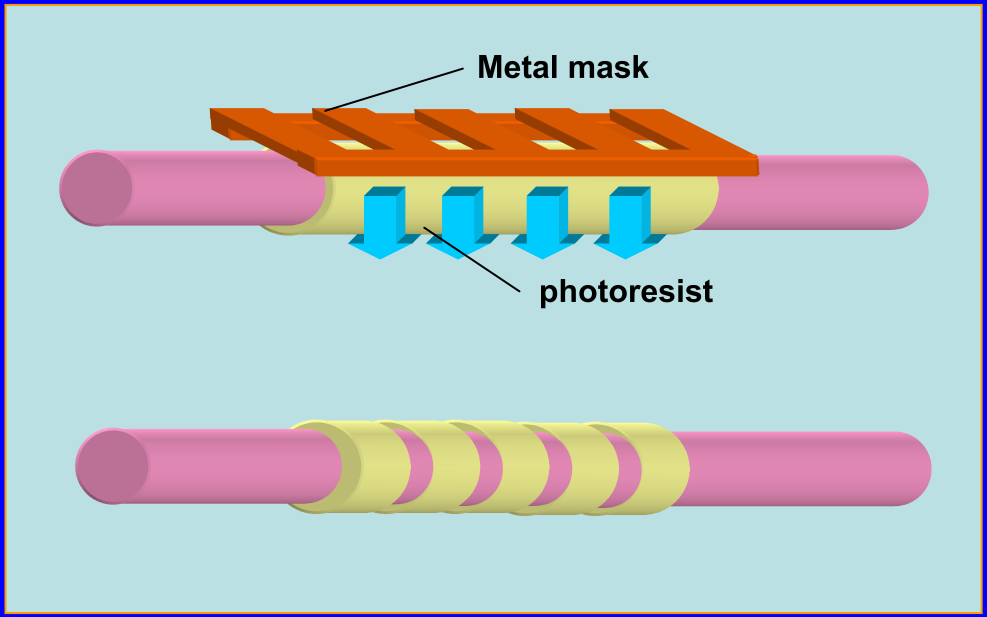


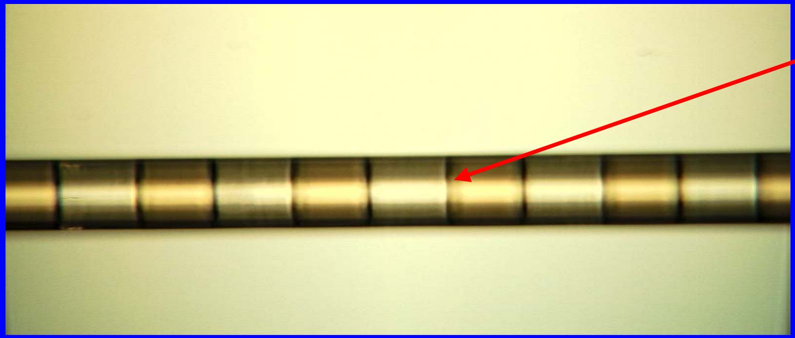
An example of sapphire etching by ICP-RIE
(www.samcointl.com)

VI. Fabrication Methods for In-Fiber Gratings in Sapphire fibers - continued

- **Plasma Etching (ICP-RIE)**

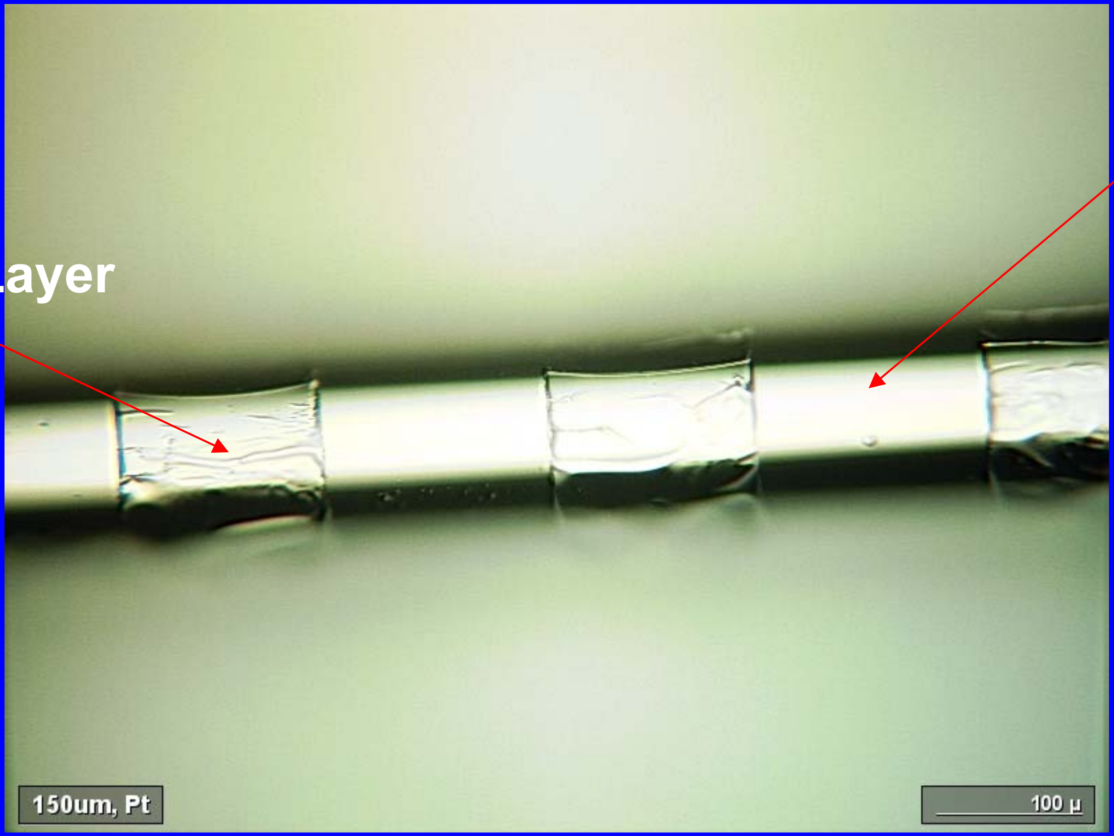






Photoresist layer

VI. Fabrication Methods for In-Fiber Gratings in Sapphire fibers - continued

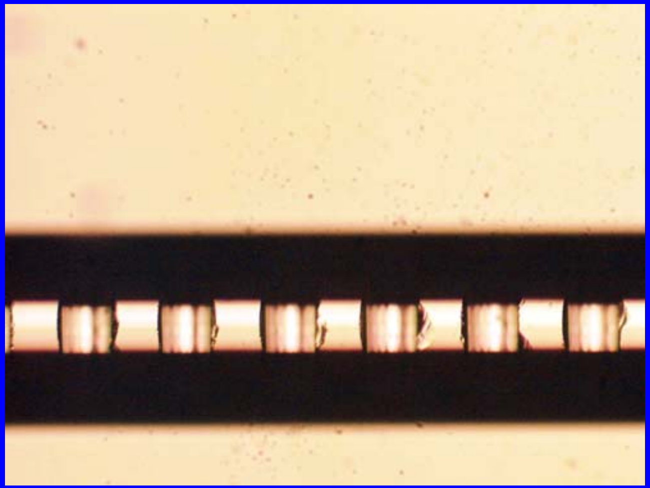


6.2 Technical Issues

- **Photolithography**
  - Special care is needed to get a clean pattern due to non-uniform thickness of photoresist.
  - To pattern FBG, e-beam lithography may be needed

- **Surface roughness may cause big scattering loss**

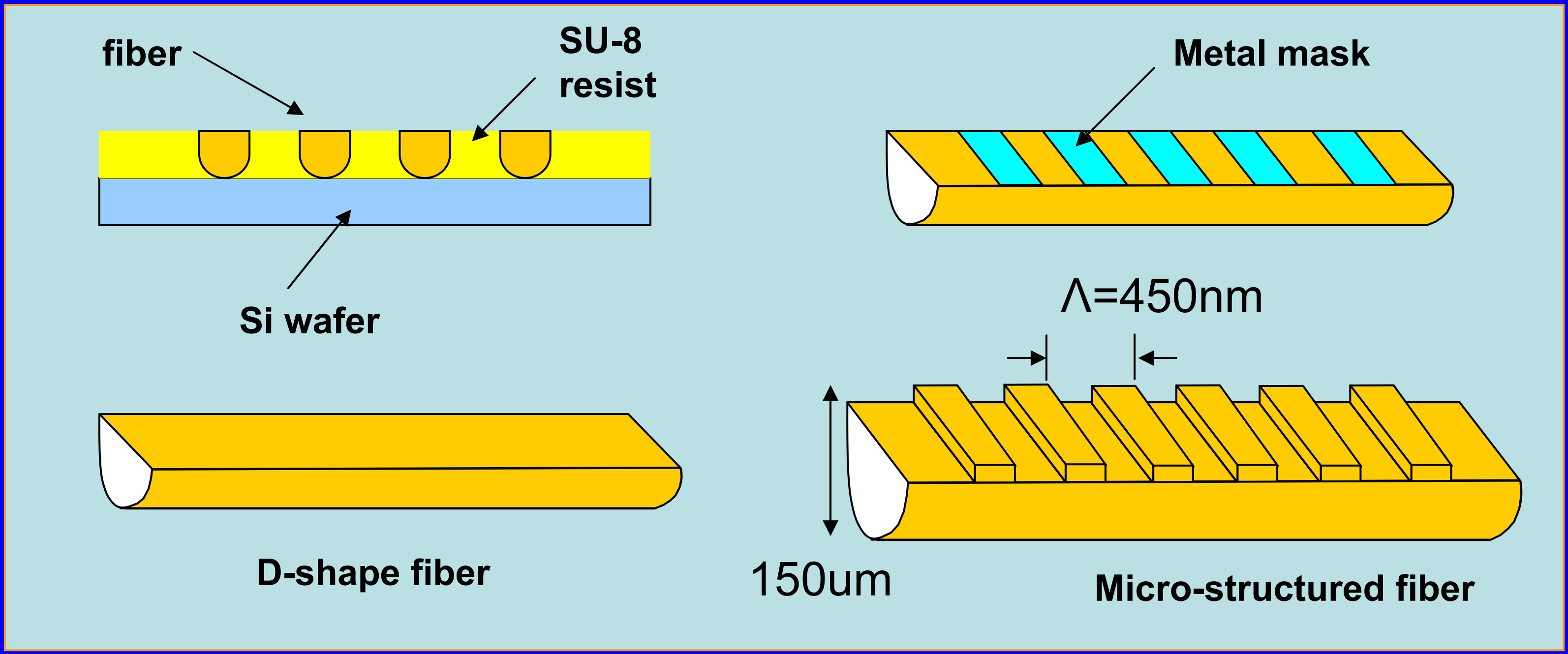
Inaccurate pattern



Surface roughness

6.2 Technical Issues

- **Advantages of using etching approach**
  - Making fibers into D-shape by fine polishing on a wafer
  - More accurate patterning and smooth surface



6.2 Technical Issues

- **Coating the cladding layer**

  -Direct deposition methods

  (MOCVD, sputtering, evaporation)

  -Polycrystalline alumina using polymer based technique

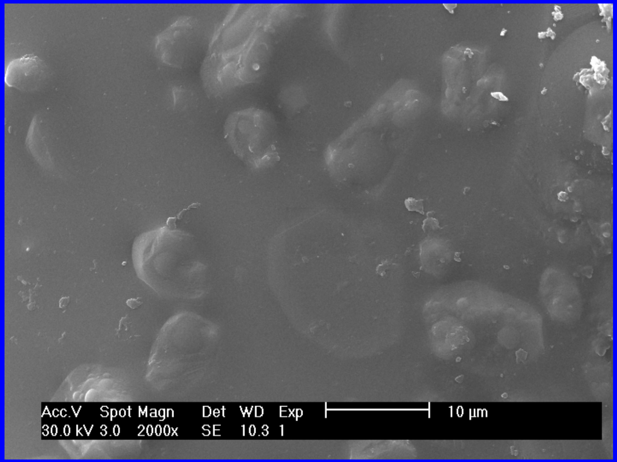
  (M.A.El-Sherif et al., Ceram.Eng.and Sci. Proc. 14, 1993)

► Provide protection layer

Reduce the scattering loss at the surface

But can not make the fibers single-moded

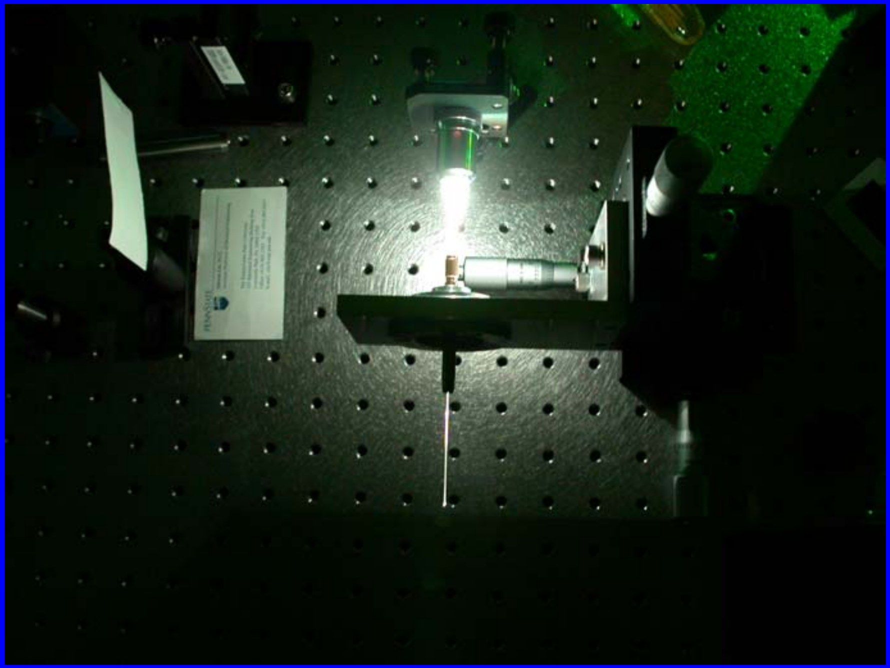
SEM image of sapphire fiber with alumina cladding

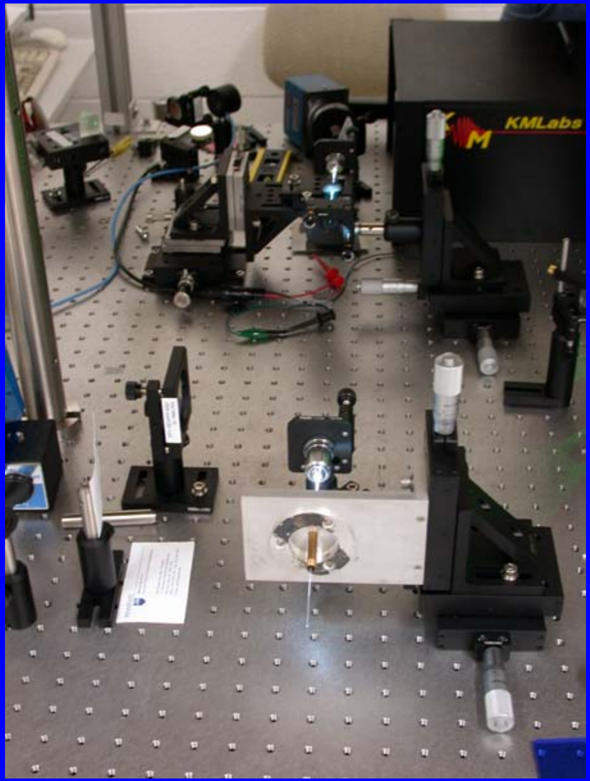


6.2 Technical Issues

- **Light source for distributed sensing**

- **Super continuum white light source using photonic crystal fiber can provide an excellent light source for distributed fiber sensing**



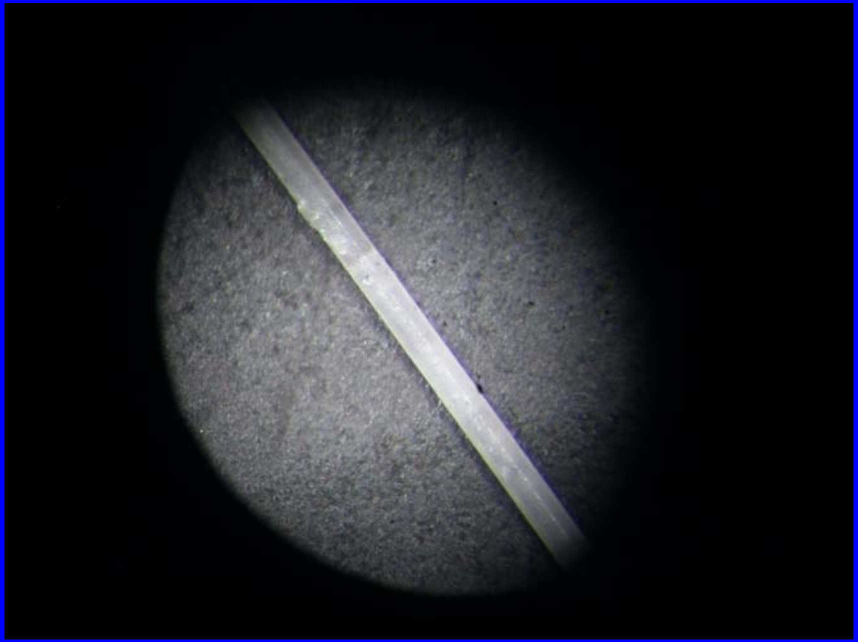


VII. Major accomplishments

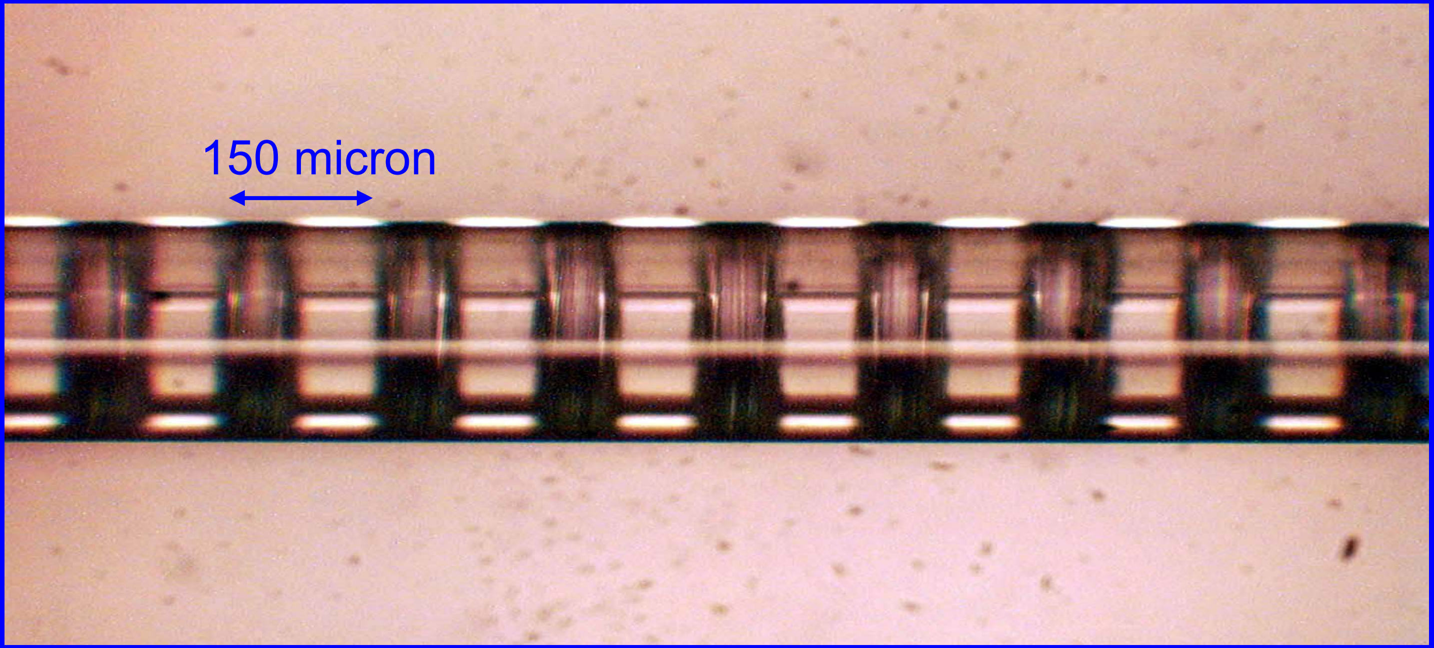
- We have accomplished all the proposed tasks

7.1 Fabricate alumina cladding layers on single crystal sapphire fibers.

- Right figure shows a single crystal sapphire fiber with alumina cladding. The diameter of sapphire core is 150 microns and the thickness of the cladding layer is around 2 microns.

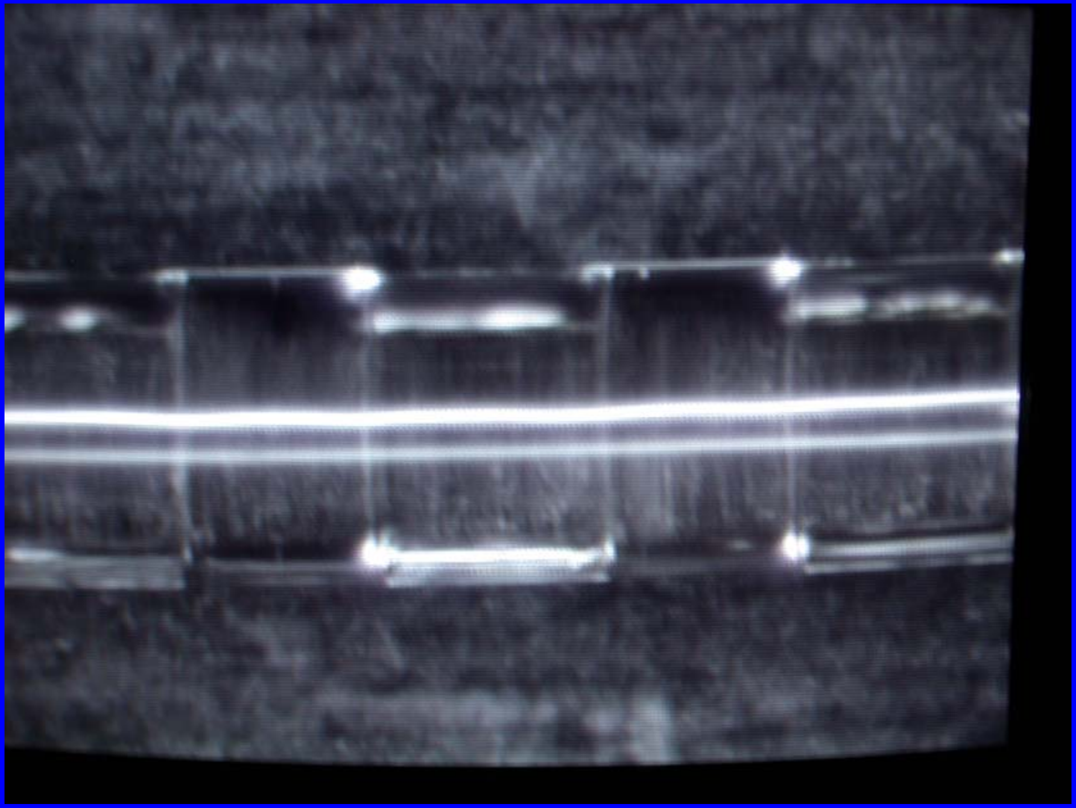


7.2 Fabricating in-fiber grating in single crystal sapphire fiber by mechanical dicing



Fabricated corrugated gratings in single crystal sapphire fiber by precise dicing

7.3 Fabricating in-fiber grating in single crystal sapphire fiber by etching

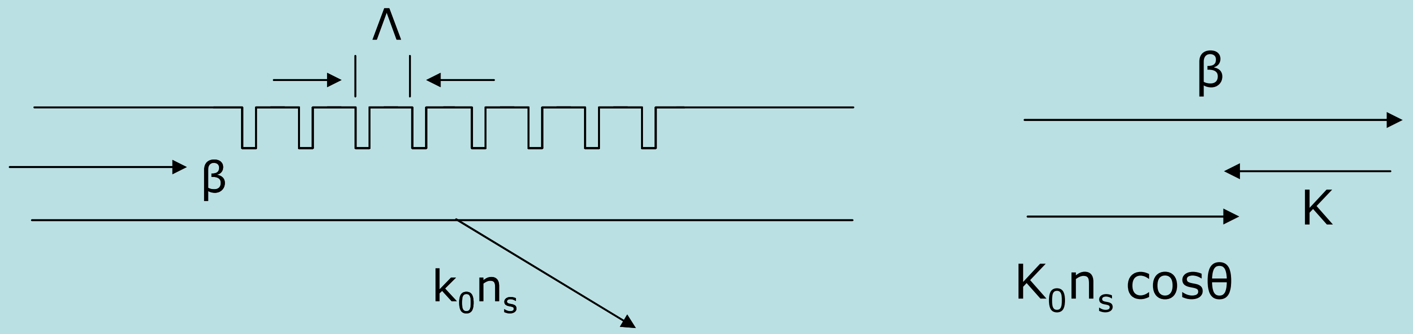


Sapphire fiber with periodic photoresistor cladding

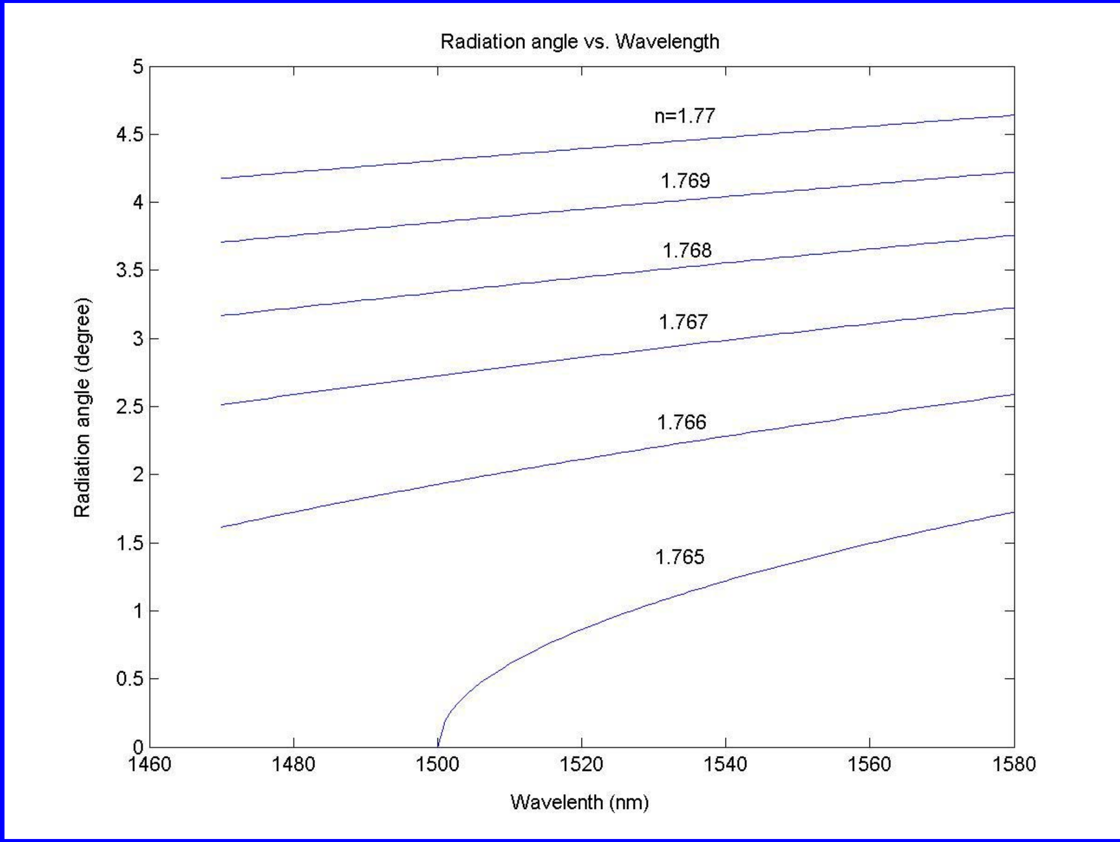
7.3 Fabricating in-fiber grating in single crystal sapphire fiber by etching - continued

A single crystal sapphire fiber with periodic coated gold layer.

7.4 Set up a mathematical model to analyze the performance of corrugated surface grating in single crystal sapphire fiber fabricated by micro-marching

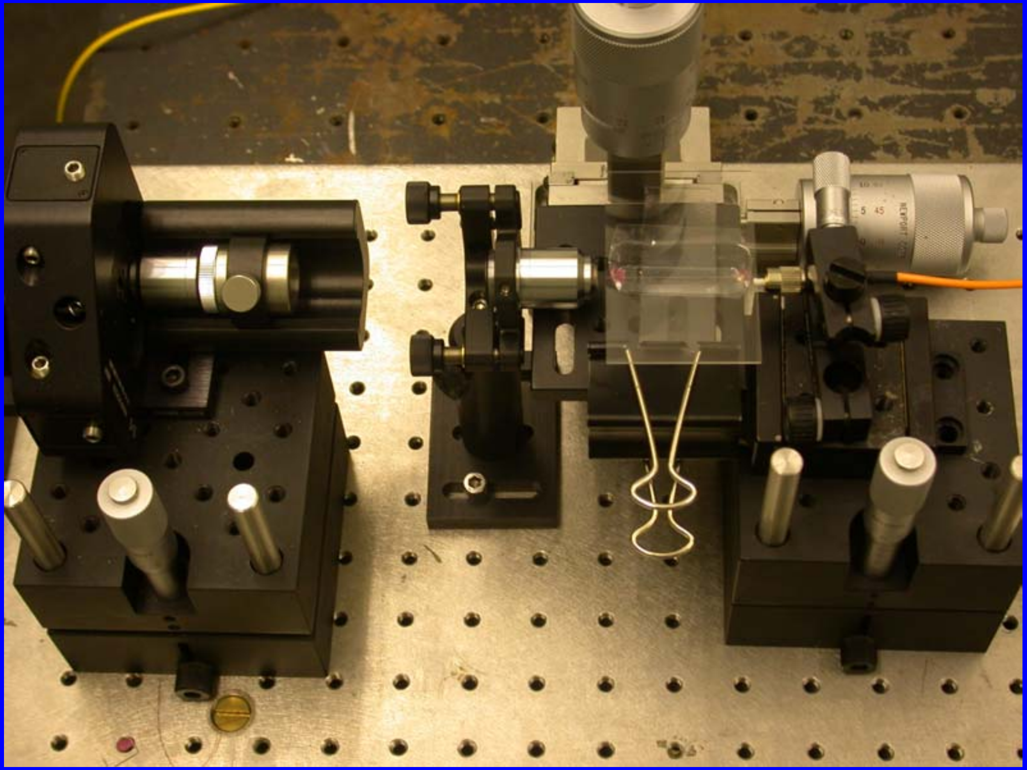


7.4 Set up a mathematical model to analyze the performance of corrugated surface grating in single crystal sapphire fiber fabricated by micro-marching - continued



Wavelength dependence of radiation mode coupling

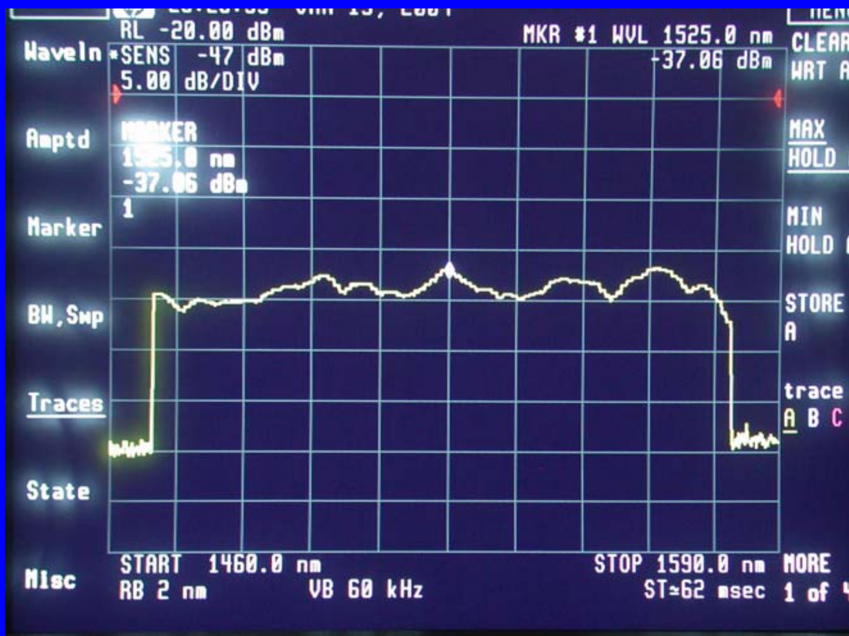
7.5 Build up an experimental system to test the performance of fiber optic sensor based on gratings in sapphire fiber



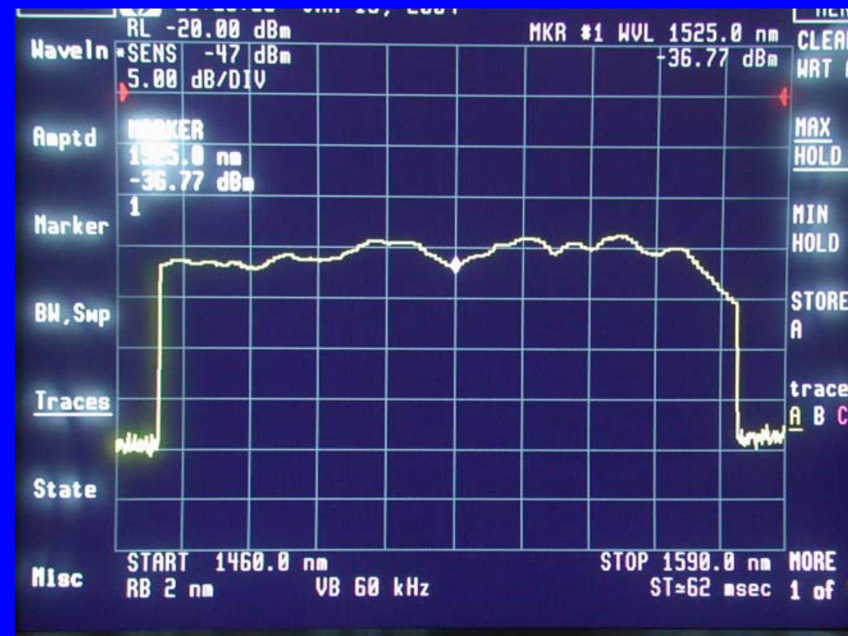
The experimental setup for measuring radiation-mode coupling effect by micro-structured gratings in sapphire fiber

7.6 Test the performance of fiber optic sensor based on gratings in sapphire fiber

The output spectrum of the sapphire fiber with surface gratings for different cladding refractive indices.



Air

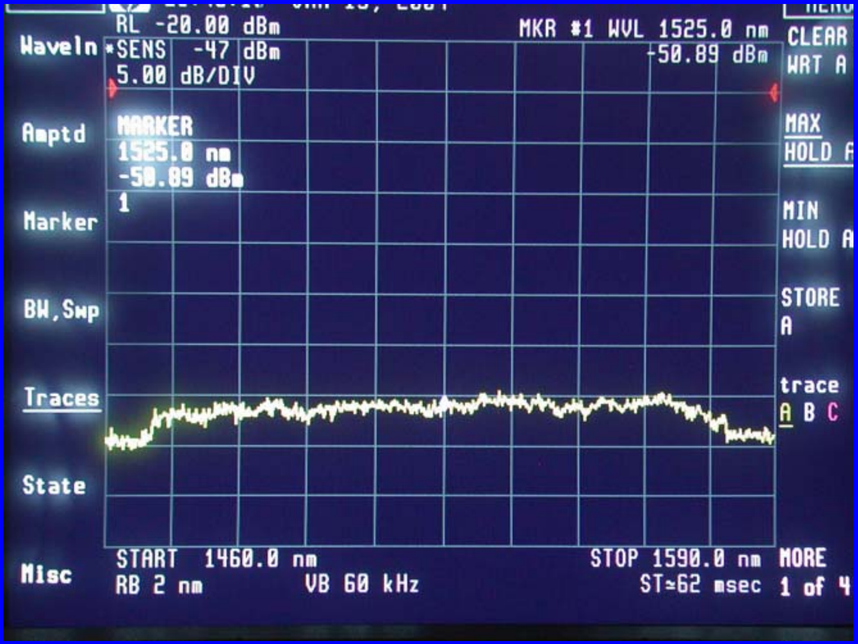


1.79

7.6 Test the performance of fiber optic sensor based on gratings in sapphire fiber

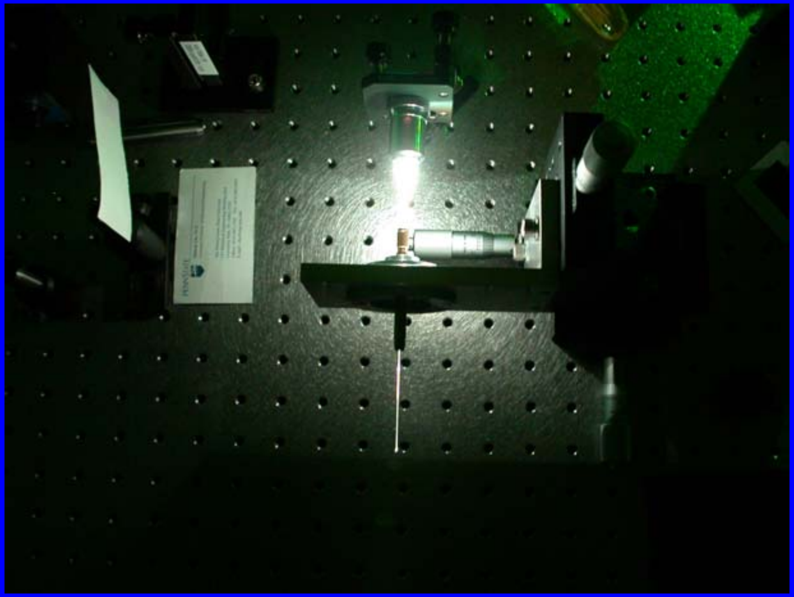
The output spectrum of the sapphire fiber with surface gratings for different cladding refractive indices.

1.795



1.80

7.7 Demonstrate the possibility of using super continuum highly broad band source



Supercontinuum white light source generation for fiber sensor systems.

VIII. Future Work Plan

- Deploy our unique distributed fiber optic sensor in a testing boiler.
- Testing the performance of the sensor for high temperature distributed sensing.
- Refine the sensor system based on testing result.
- The measured data (such as temperature distribution) from the sensor will be used to intelligently control the performance of the boiler.
- A higher burning efficiency and lower pollution emission is anticipated.